

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 6/27/97		3. REPORT TYPE AND DATES COVERED Final	
4. TITLE AND SUBTITLE The Micromechanics of High Strain-Rate Deformation and Failure of Dual-Phase Composites				5. FUNDING NUMBERS DAAH04-94-G-0086	
6. AUTHOR(S) G. Bao					
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES) The Johns Hopkins University 3400 North Charles St. Baltimore, MD 21218				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211				10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 32296.1-EG	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.				12 b. DISTRIBUTION CODE DTIC QUALITY INSPECTED 4	
13. ABSTRACT (Maximum 200 words)  Under the support of ARO (Grant number: DAAH04-94-G-0086, Solid Mechanics Program, Program Director, Dr. K. Iyer), a three-year basic research program is carried out on the micromechanics of high strain-rate deformation and failure in dual-phase composites. Three composite material systems are studied: (1) tungsten heavy alloys and tungsten-based composites; (2) ceramic particle reinforced metal matrix composites; and (3) penetrator/armor material combinations. Emphasis is placed on the relationship between the microstructure and material behavior of the dual-phase solids, aiming to provide guidelines for the design of advanced armor/antiarmor systems. The outcomes of this three-year program include: (1) A better understanding of the fundamental relationship between the high strain rate behaviors and material microstructures of metal alloys and composite materials in advanced penetrator/armor systems. (2) Formulae and design charts that quantify the effects of relative volume fractions, strain and strain rate hardening, thermal softening, and the amount of damage on the overall behavior of the dual-phase solids. (3) Micromechanical models and computational schemes that can be used to predict the dynamic behavior of the penetrator and armor materials; these models and schemes may provide a basis to link the material microstructures to ballistic performance.					
14. SUBJECT TERMS Deformation, Failure, Dual-Phase Composites Micromechanics, High Strain-Rate, Penetration				15. NUMBER OF PAGES 7	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

# The Micromechanics of High Strain-Rate Deformation & Failure in Dual-Phase Composites

FINAL PROGRESS REPORT

GRANT NUMBER: DAAH04-94-G-0086

SUBMITTED TO  
**U.S. ARMY RESEARCH OFFICE**

BY  
GANG BAO

THE JOHNS HOPKINS UNIVERSITY  
BALTIMORE, MD 21218

JUNE 27, 1997

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

THE VIEWS, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE  
THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL  
DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO  
DESIGNATED BY OTHER DOCUMENTATION.

19970820 032

## THE MICROMECHANICS OF HIGH STRAIN-RATE DEFORMATION AND FAILURE IN DUAL-PHASE COMPOSITES

G. Bao

Department of Mechanical Engineering  
The Johns Hopkins University, Baltimore, MD 21218

### *1.0 Project Summary*

Under the support of ARO (Grant number: DAAH04-94-G-0086, Solid Mechanics Program, Program Director, Dr. K. Iyer), a three-year basic research program is carried out on the micromechanics of high strain-rate deformation and failure in dual-phase composites. Three composite material systems are studied: (1) tungsten heavy alloys and tungsten-based composites; (2) ceramic particle reinforced metal matrix composites; and (3) penetrator/armor material combinations. Emphasis is placed on the relationship between the microstructure and material behavior of the dual-phase solids, aiming to provide guidelines for the design of advanced armor/antiarmor systems. The outcomes of this three-year program include:

- A better understanding of the fundamental relationship between the high strain rate behaviors and material microstructures of metal alloys and composite materials in advanced penetrator/armor systems.
- Formulae and design charts that quantify the effects of relative volume fractions, strain and strain rate hardening, thermal softening, and the amount of damage on the overall behavior of the dual-phase solids.
- Micromechanical models and computational schemes that can be used to predict the dynamic behavior of the penetrator and armor materials; these models and schemes provide a basis to link the material microstructures to ballistic performance.

### *2.0 Summary of the Most Important Results*

#### *2.1 Damage in a Tungsten Composite due to Debonding at W-W Grain-Boundaries*

A theoretical study is carried out of a tungsten-based composite sustaining debonding at tungsten-tungsten grain boundaries. The tungsten composite is comprised of a continuous network of pure tungsten grains embedded in a relatively soft tungsten-nickel-iron matrix. A damage evolution model is proposed based on the Weibull statistics

relating the fraction of debonded W-W grain boundaries to the tungsten volume fraction and the applied strains. The deformation of the alloy with debonded grain boundaries perpendicular to the tensile loading direction is simulated using a three-phase finite element cell model; both constant damage and progressive damage are considered. Systematic predictions are made for the effect of debonding on the tensile flow behavior of the tungsten composite. It is shown that the stress-strain behavior of the alloy under quasistatic tensile loading is controlled by two competing trends - strain hardening and debonding softening - both evolve with the tungsten volume fraction and the applied strains.

## *2.2 High Strain-Rate Deformation of Particle Reinforced Metal Matrix Composites*

Micromechanics analyses have been performed on the high strain-rate deformation in dual-phase composites. To gain insight, the inclusion phase is taken to be composed of spherical elastic particles, and the matrix is assumed to be elastic - perfectly plastic or power-law strain hardening; in addition, the matrix is assumed to have a power-law strain-rate hardening behavior. Systematic predictions are made of the composite flow stress as determined by inclusion volume fraction, the applied strain rate, and the strain hardening exponent and strain rate sensitivity of the matrix. It is found that the effect of strain rate is coupled with inclusion volume fraction: the strain rate hardening of the composite can be significantly higher than that of the matrix due to the constraining effect of the inclusions. A simple, user-friendly analytic formula is developed which allows one to predict accurately the rate-dependent flow behavior of the composite.

A comparison is made of the predictions of the model with the results of high strain rate experiments on a 6061-T6 Al/ $\text{Al}_2\text{O}_3$  composite. The composite contained 20% of  $\text{Al}_2\text{O}_3$  by volume, and was obtained from Duralcan Inc. Experimental measurements on this material were carried out using the compression Kolsky bar, the torsional Kolsky bar, and high-strain-rate pressure-shear plate impact. The experimental results showed that the composite had substantially greater rate-sensitivity than the matrix alloy. The predictions of the unit cell model are in good agreement with the experimental results, suggesting that a continuum description of the viscoplastic deformations is sufficient to model these materials.

## *2.3 Thermal Softening of a Tungsten-Based Composite under Adiabatic Compression*

A micromechanics analysis is made of the rate-dependent thermal softening behavior of a tungsten matrix composite containing glassy particles. Under adiabatic

compression of the composite, the elastic glassy particles thermally soften at relatively high strains, enhancing the thermal softening of the tungsten-based composite, thus reducing the strain rate sensitivity. To guide the microstructural design of the particle-modified tungsten-based composite in penetration applications, predictions are made for the stress-strain behavior of the composite under overall adiabatic compression with different temperature-dependent behaviors, sizes, volume fractions of the particle and different applied strain rates. The temperature-dependent behavior of the particles is characterized by a set of exponential functions using two non-dimensional parameters and a reference temperature. The plastic behavior of tungsten is taken to be power-law strain and strain rate hardening, and power-law thermal softening. It is found that, when only the glass particles thermally soften, the strain-rate sensitivity of the composite is reduced. It is also found that when thermal softening of tungsten is included in the model, the glass particles have little effect on the thermal softening of the tungsten-based composite provided that the volume fraction of the particles is less than 15%.

#### *2.4 A Boundary-Layer Approach for Analyzing Penetrator/Target Interactions*

A new approach for modeling penetration processes in advanced armor/antiarmor systems is being developed. Attention is focused on the dynamic behavior of the material in the boundary layer at the penetrator/target interface. The goal is to establish the relationship between the thermomechanical behavior of the penetrator and target materials and the shape of the penetrator head; this relationship may enable one to understand the controlling mechanisms in penetrator/target interactions, and to predict the ballistic performance of both the penetrator and target. This work is motivated by the observation that a penetrator made of U-3/4 Ti can keep its "nose" sharp, while a tungsten heavy alloy penetrator often forms a "mushroom" head during the penetration process.

To simplify the analysis, the penetrator/target system is divided into three zones: the penetrator, the target, and the interfacial boundary layer. The material in the interfacial zone is assumed to be heterogeneous, and undergo high strain rate plastic deformation, thermal softening, and melting. Specifically, it is taken as a mixture of the penetrator and target materials; its behavior is assumed to depend only on the position along the layer thickness. At the inner and outer boundaries of the interfacial zone the material is the same as that of the penetrator and target materials respectively. The behavior of the materials in the regions outside the interfacial zone is taken to be relatively simple: no thermal softening occurs. The geometry of the head of the penetrator is described by a simple mathematical function. The target is taken to be infinitely large in the radial

direction, with an axisymmetric cavity that is consistent with the geometry of the head and the interfacial layer. A constitutive expression for the material in the interfacial zone is developed, and a number of boundary value problems have been identified. To gain insight, the deformation in a flat boundary layer is analyzed with prescribed pressure and shear stresses applied at the upper and lower surfaces. It is believed that, by taking a new approach to the penetration mechanics problem, a fundamental understanding of the penetration processes can be gained.

### 3.0 List of Publications

1. Lin, Z and Bao, G., "Damage in a Tungsten Composite due to Debonding at W-W Grain-Boundaries," *Acta Metallurgica et Materialia*, **43**, 1765-1774, 1995.
2. Bao, G., "On Strain-rate sensitivity of metal matrices reinforced with ceramic particles", *Proceedings of the IUTAM Symposium on Micromechanics of Plasticity and Damage of Multiphase Materials* (ed. Pineau and Zaoui, 1995), pp 11-18, Kluwer Academic, London.
3. Bao, G. and Lin, Z., "High strain-rate deformation in particle reinforced metal matrix composites", *Acta Metall. Mater.*, **44**, 1011-1019 (1996).
4. P. R. LcDuc and G. Bao, "Thermal softening of a particle-modified tungsten-based composite under adiabatic compression", *Int. J. Solids Structures*, **34**, 1563-1581 (1997).
5. LcDuc, P. R. and Bao, G., "Thermal softening of glassy particle modified tungsten", in *Proc. ASME Aerospace Division and Materials Division* (ed. R. C. Wetherhold et al, 1996), AD-Vol. 51/MD-Vol. 73, ASME, pp. 497 - 505.
6. Bao, G., Rapacki, E. Jr., and Bilyk, S., "A boundary-layer approach for analyzing penetrator/target interactions," *Proceedings of 14th Army Symposium on Solid Mechanics* (eds. K. Iyer and S. C. Chou), in press (1997).
7. Chichili, D. R., and Ramesh, K. T., "Dynamic Failure Mechanisms in a 6061-T6 Al/Al<sub>2</sub>O<sub>3</sub> Metal-Matrix Composite," *International Journal of Solids & Structures*, **32**, 2609-2626, 1995.
8. Yadav, S., Chichili, D. R., and Ramesh, K. T., "The Mechanical Properties of a 6061-T6 Al/Al<sub>2</sub>O<sub>3</sub> Metal-Matrix Composite at High Rates of Deformation," *Acta Metallurgica et Materialia*, **43**, 4453-4464, 1995.

REPORT DOCUMENTATION PAGE (SF298)  
(Continuation Sheet)

***4.0 List of All Participating Scientific Personnel***

G. Bao, Associate Professor (PI)

K. T. Ramesh, Professor (Co-PI)

Z. Lin, Graduate Research Assistant, awarded M. Sc. May, 1995 and Ph.D. September 1995.

P. R. LeDuc, Graduate Research Assistant.